CHAPTER 2

Research on Thinking and Learning with Maps and Geospatial Technologies

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Identifying the Knowledge Space: Spatial Thinking

When people think of geography, they often think of students memorizing names of state capitals, landforms, and oceans. To the contrary of this popular misconception, geography is a rich discipline of study that focuses on the characteristics, relationships, and spatial patterns of the human and natural worlds. Geography includes learning about cultures, geopolitics, natural systems, resource distribution and use, and mapping spatial data to better understand the world. As the U.S. national geography standards illustrate, a geographically informed person is someone who views the world ***spatially***. Understanding the way in which the world is organized spatially is critical to learning and doing geography.

The 18 national geography standards presented in *Geography for Life*, 2nd Edition (Heffron and Downs 2012) are organized under six Essential Elements: The World in Spatial Terms, Places and Regions, Physical Systems, Human Systems, Environment and Society, and the Uses of Geography. For the purpose of this chapter, we focus our review of the literature within Essential Element 1, *The World in Spatial Terms*, which includes three standards:

- How to use maps and other geographic representations, geospatial technologies, and spatial thinking to understand and communicate information.
- How to use mental maps to organize information about people, places, and environments in a spatial context.
- How to analyze the spatial organization of people, places, and environments on Earth's surface.

Together the three standards focus on a fundamental way of thinking *about* the world and *within* the world. **Spatial thinking** is a combination of knowing about spatial concepts and types of relationships and patterns that occur in the world; using tools, both internal and external, that represent spatial data; and being able to reason about or with spatial data or phenomena (National Research Council [NRC] 2006). Spatial thinking is a type of thinking that *all* people possess and use to greater or lesser extents in their everyday lives and careers. While not unique to geography, spatial thinking is a cornerstone of the discipline and essential to the teaching of geography to novice learners (Hanson 2004).

While there is almost fifty years of research on spatial thinking, it has been notably difficult to define and measure it, and arguably even more difficult to foster spatial thinking among students in actual classroom settings. There is a wealth of research on spatial thinking tasks (outside the regular classroom), especially studies that compare novices to experts and males to females. Overall, however, the body of literature is fragmented for several reasons. The research studies originate in many different fields of study (e.g., geography education, cognitive psychology, learning sciences, and neurosciences) and thus, emphasize different elements of spatial thinking. Researchers have used a wide variety of approaches to measure aspects of spatial thinking, but the spatial tasks that are utilized vary so greatly from study to study that comparison of the findings across multiple research studies can be problematic. In many cases, the specificity of the task and the context in which it was measured prevents findings from being generalized. This is especially true when trying to make sense of what happens across a developmental time span or in real-world settings, such as the classroom. For example, cognitive psychologists have focused their efforts on table-top and computer-generated tasks to better understand spatial visualization and orientation, while many geography education researchers focus on wayfinding and navigational tasks using spatial representations (e.g., maps). Neuroscientists tend to focus more closely of aspects of brain functionality as it relates to performing spatial thinking tasks.

All of these disciplines contribute significantly to our understanding of spatial thinking as a whole, somewhat like piecing together a giant jigsaw puzzle. Yet, even given the decades of research on the topic, our puzzle is far from complete. Many pieces have been assembled but there is a notable lack of systematic effort to make connection between the seemingly disjointed parts. Regardless of the disparities within the current body of literature, there is a great need for learning progressions research to better understand how and when spatial concepts, tools and processes of reasoning begin to emerge and evolve in young children into adulthood, and potentially how instructional materials and teaching strategies can better support students in more sophisticated ways of thinking spatially. While, individually, many of these research studies have certainly contributed significantly to our understanding of spatial thinking, as a combined body of literature, we lack the coherence needed to make use of this research to improve classroom practice.

The rest of this chapter takes a closer look at existing frameworks that communicate the concepts, tools and processes related to spatial thinking and how we might build from the frameworks to produce learning progressions. We look at how we might use the existing research to define the upper and lower anchors of a learning progression within the spatial thinking domain, and then how to determine measurable progress variables between these anchor points. We conclude with special considerations that may affect how one defines the Lower and Upper Anchors of a spatial thinking progression.

Defining the Domain of a Spatial Thinking Learning Progression

A major undertaking at the start of learning progressions research is to identify the domain of the progression. The broad expanse in which we can find spatial thinking complicates this process to some extent. As previously described, spatial thinking encompasses a wide variety of constructs and spatial practices. In this chapter we focus on spatial thinking as defined by NRC (2006), but also point to specific frameworks for spatial thinking developed within the geography education community. We chose the NRC Framework because it represents considerable consensus regarding the concepts, tools, and reasoning processes of spatial thinking, even though the limited systematic research into these concepts, tools and reasoning processes that make up the framework has been noted (Bednarz, Heffron, and Huynh 2013). There are several other equally valid frameworks that are important to consider, especially as many of these frameworks have been created by geographers with substantial experience in spatial thinking research (see Table 1). All of these frameworks capture the array of constructs and practices essential to spatial thinking, and thus, are useful tools to consult when defining the domain of a progression, and also situating the progression within the larger backdrop of spatial thinking as a whole.

Clearly articulating the domain of the progression can be useful for understanding what is and what is not being investigated and explained by the learning progression. Let us look at an example of why this process is important using spatial representations from the NRC framework. Spatial representations include both internal and external representations; internal representations being mental mapping and mental modeling, while external representations being a combination of concrete or technology-based maps and models. If one was interested in better understanding internal representations, like mental mapping, a learning progression would then target this construct. However, if one was interested in geospatial technologies, a learning progression might hone in on external representations like GIS mapping, or computer modeling. While both would investigate types of spatial representations, they would result in vastly different learning progression domains. To complicate matters further, a learning progression might focus on the "what" or substance of the representations, or a learning progression might focus on the process and skills for creating and/or using representations. So a learning progression could take the form of descriptions of how spatial representations themselves evolve, or as a description of how creating or using spatial representations evolve, or even a combination of the two. Within this example of spatial representations, there are many possible learning progressions to be developed. Consequently, situating the substance, or domain, of a progression becomes an important task at the outset of learning progression research.

Learning Progression Anchors and Progress Variables

Every learning progression has both a lower anchor and an upper anchor; the lower anchor represents the emerging knowledge students have as novice learners of a construct or practice, and the upper anchor is a depiction of what learners should know and be able to do after learning has occurred. The goal of the learning progression is to not only define the anchor points clearly, but more importantly to uncover the intermediate understandings that occur between them (Duschl, Schweingruber, and Shouse 2007).

Upper Anchor: The upper anchor is typically representative of societal expectations of learning a topic, and so it is naturally related to learning goals captured by national and/or state standards. The upper anchor of a learning progression does not necessarily have to replicate education standards, but it should depict the depth of knowledge that could reasonably be expected on a topic at given age levels. *Geography for Life, 2nd Edition* and documents such as the NRC (2006) report are important resources to guide development of the upper anchor. Yet, even more important to defining the upper anchor is the inclusion of expectations we may have for educating citizens, or for educating future experts in the field. Either way, there needs to be a consideration of what are the most essential constructs or practices that we would like *all* students to be able to know or use after they have learned about a topic. Sometimes the upper anchor might draw from several different education standards, or might bridge different subfields within the geography or spatial thinking disciplines.

Table 1. Spatial Concepts Frameworks. This table originally appeared in Mohan and Mohan (2013) and is reprinted here with permission from National Geographic.

Learning to Think Spatially, NRC 2006	Building on work by Golledge et al. 1995, 2002, 2008a; Adapted by Jo and Bednarz 2009	Gersmehl and Gersmehl 2009, 2007, 2006	Janelle and Goodchild 2011	Cognitive Psychology (general reference; see Bednarz and Lee 2011; Golledge, Doherty, and Bell 1995)
Concepts of Space Primitives of identity Spatial relations **Tools of Representation** Internal External **Processes of Reasoning** Extracting spatial structures Performing spatial transformation Drawing functional inferences	**Spatial Primitives** Identity/Name Location Magnitude Time/Duration **Simple Spatial Relationships** Distance Direction Connectivity and linkage Movement Transition Boundaries Region Shape Reference Frame Arrangement Adjacency Enclosure **Complex Relationships** Distribution Pattern Dispersion/ Clustering Density Diffusion Dominance Hierarchy/Network Association Overlay/Layer Gradient/Profile/Relief Scale Projection Buffer	**Location** Conditions Connections **Modes of Spatial Thinking** Comparison Aura Region Hierarchy Transition Analogy Pattern Spatial Association **Spatio-Temporal Thinking** Change Movement Diffusion (expansion or contraction) Spatial Models	Location Distance Neighborhood and Region Networks Overlays Scale Spatial Heterogeneity Spatial Dependence	**Visualization** Ability to mentally manipulate, rotate, twist or invert two- or three-dimensional visual stimuli. **Orientation** Ability to imagine how a configuration would appear if viewed from a different orientation or perspective. **Spatial Relations** Ability to estimate or reproduce distances, angles, linkages and connectivities; to develop spatial hierarchies in which nearest-neighbor effects are prominent; to remember sequence and order as in cues along a route; to segment or chunk routes into appropriately sized units that facilitate memorization and recall; to associate distributions or patterns in space; and to classify and cluster information into meaningful spatial units such as regions.

Importantly, the upper anchor is often a reflection of vision that geography educators have for student learning, and can be based on many years of working in the classroom and with other geography educators. It should set high expectations for learning, but also ones that are reasonable and achievable by students.

Lower Anchor. Existing literature in the field, however incomplete it may be, is a necessary resource for understanding the lower anchor.

Oftentimes, the emerging concepts and/or skills at the lower anchor that contribute to upper anchor understanding are not obviously connected and may only later be revealed to researchers once data is examined from novice learners. When looking across several studies it is possible to begin identifying patterns in student thinking with respect to a spatial thinking construct or practice. In science education, for example, Rosalind Driver and colleagues reviewed considerable literature on student learning of science concepts and then produced numerous books and articles to summarize what they found for the science education community. Their work helped to paint a picture of student ideas in different domains, which naturally lent itself to learning progressions work (e.g., Driver, Asoko, Leach, Scott, and Mortimer 1994; Driver, Squires, Rushworth, and Wood-Robinson 2013). While spatial thinking does not have similar resources available, the NRC (2006) report is an excellent place to start, along with other efforts to begin summarizing students' ideas about spatial thinking among young children (e.g., Liben 2006, 2002; Mohan and Mohan 2013; Newcombe and Huttenlocher 2000; Uttal 2000).

To add to spatial thinking's nebulous nature is the lack of consensus among researchers in the field regarding its temporal development, especially as it relates to very young pre-K and elementary age students. There is a notable debate about the capabilities of these very young children that is significant to consider in learning progressions research. The research literature on spatial thinking is complicated by two competing schools of thought regarding its development in young children. On one side, nativist researchers believe that spatial thinking develops innately within young children with little to no guidance from knowledgeable adults, and in some cases these children can engage with fairly sophisticated spatial tasks (see, for example, Newcombe and Huttenlocher 2000; Blaut 1997; Blaut and Stea 1974, 1971).

On the other side of the debate, constructivist researchers assert that while spatial thinking can develop early in life, full realization or mastery of this type of thinking cannot occur until later in life (see, for example, Liben and Downs 1993, 1989; Piaget and Inhelder 1967). The debate primarily stems from Piaget's Three Mountain Task, which demonstrated that students under nine or ten years old struggled with perspective-taking on spatial tasks, leading Piaget and colleagues to develop a topological to projective/Euclidean progression of spatial thinking from early childhood to upper elementary; however, similar perspective-taking tasks have shown that even three-year-olds have the ability to view locations of items from different perspectives (Newcombe and Huttenlocher 2000, 118-125). The Piagetian spatial tasks set the stage for researchers to question the spatial abilities children were truly capable of in their younger years, a debate that has not been resolved. Regardless, these two different camps within spatial thinking research, that is, the nativist and the constructivist, both suggest that spatial thinking is an innate ability that emerges in young children; however, constructivists believe that it cannot develop fully until a child has reach a certain level of cognitive maturity and has both formal and informal opportunities to learn to think spatially.

Within spatial thinking research, mapmaking and map reading boasts a great deal of research targeting the lower anchor of learning with substantial attention given to discovering the earliest appearances of making and using simple maps to locate objects. There is substantial debate regarding what young children can and cannot understand about maps. Many researchers (e.g, Blaut 1997; Blaut, Stea, Spencer and Blades 2003) have stressed that young children are capable of understanding aspects of maps from an early age. More recently, psychologists have demonstrated that children as young as 2.5years of age can use some of the spatial properties of very simple maps of locations of objects in a room (e.g, Winkler-Rhoads, Carry, and Spelke 2013).

However, some researchers have urged caution in over interpreting these findings (e.g., Liben and Downs 1993), suggesting that these demonstrations of early competence, although impressive and important, are not demonstrations of fully-fledged map-reading abilities (e.g., Liben 2002), Most of the psychological studies with young children have focused on single skills, such as detecting the relation between a map or model and the space that it represents. These studies do not consider map reading as a systematic activity involving many different cognitive abilities, but instead use a more reductionist approach that isolates individual abilities. Acquiring a deeper, more conceptual understanding of maps is a lengthy developmental phenomenon that depends on substantial learning and experience.

Mohan and Mohan (2013) reviewed the body of research on spatial thinking as it relates to mapmaking and map interpretation and found that while there were a great many efforts made to understand the lower anchor characteristics among young children, there still remained significant gaps in the research, both in terms of the substance of the findings and also with the methodology and spatial tasks utilized (discussed later in this chapter). Table 2 summarizes key findings on several spatial constructs with respect to very young, novice learners, and is one resource that can serve as a starting point when developing initial characteristics of lower anchor thinking.

Progress Variables. Simply defining the upper and lower anchor points, however, does not provide enough direction to dig into the meat of the learning progression—the design of assessments and curriculum that will help uncover the intermediate understandings between anchor points. After hypothesizing both the upper and lower Anchor points, a logical next step would be to figure out a way to measure the constructs or practices that are included. The measurable elements of a progression are usually termed progress variables. Ideally progress variables are chosen because they are 1) big ideas or key constructs and practices within the discipline, and also because 2) they can be operationalized to measure knowledge at both the novice and expert levels. Corcoran, Mosher, and Rogat summarize progress variables as "critical dimensions of understanding and skill that are being developed over time" (2009, 15).

In science education, for example, learning progressions might utilize scientific principles or cross-cutting concepts as progress variables, such as structure, function, matter, energy, change over time, scale, hierarchical organization, etc. Similarly, when spatial researchers are asked what it means to think spatially, they tend to explain it using a set of fundamental constructs and practices that encompass a great deal of spatial thinking more broadly (e.g., location, direction, distribution, scale, hierarchy; see Table 1). Identifying the potential progress variables within a progression is a matter of unpacking the upper anchor and tracing it back to emerging ideas from young children. What constructs might bridge between the two anchor points and is this construct measurable? If so, then it is likely a good candidate as a progress variable in the learning progression.

Table 2 summarizes a plausible list of progress variables that, while not named progress variables by researchers, have been utilized to examine spatial understanding at different age levels. When Mohan and Mohan (2013) mapped the existing literature onto the spatial frameworks outlined in Table 1, they were able to show the potential of spatial constructs serving as progress variables for a learning progression (see publication for full review). The potential progress variables are both enduring constructs in the field of spatial thinking, and they have demonstrated the ability to be operationalized and measured at different age levels.

The progression of concepts in Table 2 is based upon, in many cases, just one or two studies, but it allows researchers to consider the possible age levels to target in establishing upper and lower anchors for progress variables. For example, primitive spatial concepts, such as location, would likely have an age span from ages three to upper elementary while complex spatial concepts, such as overlay, might more appropriately be targeted between upper elementary through high school or adulthood. Golledge, Marsh, and Battersby (2008b) developed a table that shows what the research recommends in terms of introducing spatial concepts to young children. We have reproduced this table, with some adaptations, in Table 3. While the existing literature contains many gaps, using what research we have and geographers' best guesses we can make fairly good predictions at when children are primed to learn spatial concepts. The research tends to focus on very young children, so understanding learning in the upper elementary and middle grades is certainly an area in which learning progressions has great potential to illuminate.

Putting it Together: An Illustrative Case

In order to illustrate the development of upper and lower Anchors and progress variables, we will use a hypothetical learning progression we call *Spatial Aspects of Conflict* as an illustration of how this process might work. We are using this illustration simply as a way to think through the process of designing a hypothetical progression for spatial thinking, but it is clearly only representative of the initial stages in a much more complex iterative design process.

Let us say that we would like to develop a learning progression on student understanding of the spatial aspects of conflict. As geography educators we believe that understanding spatial elements of conflict is critical for 21st century citizenship but we would like to better understand how students' understanding of this construct can evolve to maturity before they leave high school.

For our upper anchor we state that all students graduating from high school need to be able to understand the role that resources, such as water, oil, and natural gas, play in conflicts around the world. We would like students to be able to understand news reports and newspaper articles on the topic of worldwide resource conflict once they leave K-12 education so that they can be knowledgeable citizens—not experts—on the topic.

Table 2. Synthesis of the progression of spatial concepts ages 3-12. Modified from Mohan and Mohan (2013). Reprinted with permission from National Geographic Society.

Spatial Concepts	Student Understandings and Possible Misconceptions and Challenges		
	Ages 3-6 (Pre-K through Grade 1)	**Ages 7-9 (Grades 2-4)**	**Ages 10-12 (Grades 5 and 6)**
Identity and Location	Students in this age group can typically identify places on maps, landscape features on maps and aerial photographs, and can locate familiar places on maps. While children at this age can identify places, they may be limited by vocabulary development. Students might also use landmarks as a way to identify where places or items are located on a map, but they can easily confuse locations on maps if the map is not well aligned to their real world. **Studies of Interest:** Blades and Spencer 1990; Blaut and Stea 1974, 1971; Blaut, Stea, Spencer, and Blades 2003; Bluestein and Acredolo 1979; Downs, Liben, and Daggs 1988; Huttenlocher, Newcombe, and Vasilyeva 1999; Liben 2008; Liben and Downs 1993; Presson 1982; Sowden, Stea, Blades, Spencer, and Blaut 1996	Students can accurately locate places and landscape features on a map, but perform better with familiar locales as opposed to foreign locales. Map alignment issues also improve at this age. However, students inconsistently use landmarks to verify locations. **Studies of Interest:** Blaut and Stea 1971; Golledge, Battersby, and Marsh 2008a; Kastens and Liben 2010, 2007	Students need to be primed to use all the resources available to determine locations, and encouraged self-explanation of decisions, to cue thinking more about landmarks, distances, and directions. Students do not readily use map scales, metric distances, or cardinal directions to help determine locations, but can do so if prompted during instruction. Accuracy on these tasks is better for familiar places and becomes less accurate for more foreign or large-scale tasks. **Studies of Interest:** Blaut and Stea 1971; Golledge and Stimson 1997; Liben 2008; Liben and Downs 1993; Tretter et al. 2006
Magnitude	Students seem to innately understand magnitude of objects (bigger, smaller), but they might confuse the size of an object with the number of objects (numerosity). **Studies of Interest:** Golledge, Battersby, and Marsh 2008a; Mix 1999; Rousselle, Palmers, and Noel 2004		
Distance and Direction	Understand relative distance, such as near, far, next to, and can begin using relative direction on maps, such as navigating mazes. Struggle with knowing which way to "hold a map" and easily get confused if it is not aligned to the real world; Students also do not intuitively think about distances without being prompted to do so. **Studies of Interest:** Blades, Sowden, and Spencer 1995; Blades and Spencer 1987; Liben 2008; Liben and Downs 1993; Rutland, Custance, and Campbell 1993	This is a transition period between topological (e.g., near, far) concepts of distance to metric measurements; by 4th grade, students should readily use metric distances. They will still need guidance to transition to metric measurements though. Students also frequently use landmarks and relative direction, but some ready to learn cardinal directions. **Studies of Interest:** Kastens and Liben 2010	
Frames of Reference and Perspective Taking	Children at this age view the world from an egocentric frame of reference (i.e., how they see the world rather than how another perspective might see it, such a bird flying over a house). **Studies of Interest:** Newcombe and Frick 2010; Newcombe and Huttenlocher 2000;	Students can begin to understand grid systems (coordinate system) and begin learning absolute location. Students might get distracted by features that are not useful and neglect useful features on maps. **Studies of Interest:** Bell 2000; Liben 2008; Kastens and Liben 2010; Newcombe and Frick 2010	
Scale	Students at this age can handle scale better using smaller, familiar spaces, such as a classroom. Students do not have a systematic way to handle scale- they cannot move between scales easily, such as the size of the school in real life v. the size of a school depicted on a map. **Studies of Interest:** Liben 2008; Uttal 2000		
Symbols	Abstract, unrelated symbols are not understood well at this age level. Students might also confuse the colors used on representations and expect those colors to be the same in the real-world (e.g., a red road on a map should be red in real life). **Studies of Interest:** Liben 2009, 2008; Myers and Liben 2008	During this age, students transition between iconic real-world symbols to abstract symbols, but they still make significant errors; explicit guidance needed on what symbols mean. **Studies of Interest:** Golledge, Battersby, and Marsh 2008a; Liben 2009, 2008; Myers and Liben 2008	Students can use abstract symbols and understand symbols do not always "look like" the referent. **Studies of Interest:** Golledge, Battersby, and Marsh 2008a; Liben 2009, 2008; Myers and Liben 2008
Hierarchies		Concept of hierarchy (or nesting) is not well established innately with this age group, but can possibly be introduced with close guidance. **Studies of Interest:** Lowes 2008	
Overlay and Other Complex Spatial Tasks			About half of all 6th grade students incidentally understand the concept of overlay without formal instruction Guidance using map overlays can likely improve student success. Students can also move onto complex spatial concepts such as distribution, patterns, overlays, and projection with support if mastery of the basic spatial concepts of location, distance, direction, boundaries, regions achieved. **Studies of Interest:** Battersby, Golledge, and Marsh 2006

Table 3. Spatial Thinking Concepts by Grade. Adapted from Golledge, Marsh, and Battersby 2008b, 98.

	Geospatial concept	Grade					
		K	1	2	3	4	5
Primitives	Identity/Name	X	X	X	X	X	X
	Location (Relative)	X	X	X	X	X	X
	Magnitude	X	X	X	X	X	X
Simple Spatial	Distance (Relative)		X	X	X	X	X
	Direction (Relative)		X	X	X	X	X
	Shape		X	X	X	X	X
	Symbol (Real-World)		X	X	X	X	X
	Boundary			X	X	X	X
	Connection			X	X	X	X
	Reference Frame/Coordinate Grid				X	X	X
	Distance (Metric Measurement)				X	X	X
	Direction (Cardinal Directions)				X	X	X
Complex Spatial	Network				X	X	X
	Hierarchy				X	X	X
	Distribution				X	X	X
	Pattern				X	X	X
	Symbol (Abstract)					X	X
	Map Projection						X
	Scale						X

While we have identified the goal for student learning and the upper age range for our progression (i.e., 12th grade), we have yet to hone in on what our learning progression will be about specifically, the concepts and skills the learning progression will encompass, and the lower age range of children we will investigate (and how this age was determined).

The next step would be to decide what elements of spatial thinking we believe will play the most significant role in understanding spatial aspects of conflict over resources. This list of concepts should be fluid across the iterative design process inherent in learning progression work, but needs to be initially hypothesized to give us a reasonable starting point. The conceptual frameworks in Table 1 are one useful resource for making decisions about these constructs, along with *Geography for Life*, 2nd Edition and NRC (2006).

After reviewing the literature on spatial aspects of conflict, we determine the most significant spatial concepts that ultimately contribute to understanding conflict over resources include 1) location, 2) boundaries, 3) settlement patterns and 4) movement of people. We might also suspect that 5) networks and 6) hierarchies become particularly important as students develop more sophisticated understanding. We have now identified six spatial concepts that we believe are critical in our hypothetical learning progression, are representative of big ideas in spatial thinking, and are also ones we can envision measuring in both a 12th grader and a younger age level of student. While six progress variables are possibly too many, the initial list will give us direction to design assessments and instructional resources.

Given the six constructs we have chosen, what age would make the most sense for the lower anchor of the progression? At this point the existing research literature with young learners becomes especially important. Tables 2 and 3 summarize what existing spatial thinking research says about the emergence and appropriateness of some spatial concepts at particular grade levels, but these tables are certainly not exhaustive. Given our hypothetical concepts it appears that we may be able to investigate students ideas about location as young as kindergarten age, but all concepts—location, boundaries, networks, etc.—are developing and/or emerging by upper elementary. This might be a reasonable starting point for the lower anchor. Now we have determined that our initial round of development of assessments and instructional resources should examine students as young as grade 4. From existing literature we can expect that students have more advanced understanding of location, but may continue to struggle with map scales and cardinal directions, especially in unfamiliar regions around the world. They will likely be a very novice learner when it comes to concepts of hierarchy and networks.

The case described above is not intended to oversimplify the messy reality of defining the upper and lower anchor points and progress variables. This process involves significant back-and-forth negotiation among members of a research team, and lots of documents ending up in the recycling bin before even an initial learning progression is proposed and agreed upon. The case study does, however, show how existing resources on spatial thinking can be utilized to make the best guess possible at the outset of learning progressions work. Our review of the literature on spatial thinking has shown that great strides have already been made in this field that provide a solid foundation for learning progressions work to begin. Somewhat like someone finishing the border on your jigsaw puzzle for you, but leaving the middle parts for you sort out!

Process-Oriented Progress Variables

So far this chapter has focused for the most part on frameworks that have been developed to capture spatial thinking and research related to specific spatial constructs. One of the issues that has plagued learning progressions work in science education is the overemphasis on understanding the development of scientific ideas, with less research on the development of scientific practices. It is arguably easier to develop a learning progression on science concepts (e.g., matter, atomic theory, carbon cycle, water cycle, genetics, etc.) as opposed to one that focuses on the development of a practice, which may be one reason for the inequity in the learning progressions work so far. Even so, several science educators have given a great deal of thought to what it might look like to describe the development of a science practice. Schwarz, Reiser, Davis, et al., (2009) are working on a scientific modeling learning progression, while Nancy Songer, Amelia Gotwals and colleagues (2013, 2012, 2009) are developing a progression on evidence-based explanations. Given the nature of spatial thinking and the process-oriented aspects of it, learning progressions in spatial thinking will need to take on the challenge of describing how processes (e.g., map reading, mapmaking, navigation, spatial models, and spatial transformations and analyses) develop over time. As with science education a learning progression describing the development of a process or practice in spatial thinking will always be in the context of some spatial construct.

There are three processes or practices in spatial thinking that we would like to note as particularly important considerations for future learning progressions research, and of particular interest to geography educators. Those are: mapmaking, map reading and navigation, and using geospatial technologies. There is certainly overlap among the three, depending on how each is being used (e.g., GIS can be used for mapmaking or navigation, etc.). However, the spatial reasoning processes involved in traditional mapmaking, such as children's free-hand maps of a particular place, and the reasoning processes involved in creating a map using GIS, are very different, and thus would result in different types of assessment tasks and likely very different learning progressions. We call these out separately because we see them as a culmination of the spatial concepts, tools of representation, and process of spatial reasoning (NRC 2006) and thus they present in many ways the enduring practices of the discipline of spatial thinking in the geography education community. Like spatial concept development, there is existing research to build from in each of these areas. There are more studies that focus on either younger children (with mapmaking and navigation) and with secondary or adult populations (with navigation and geospatial technologies), but piecing together the messy middle is where we lack current research.

Mapmaking. A significant volume of publications have been produced over the last forty years in regards to the development of "mapmaking" in children (e.g., Lowes 2008; Weigand 2006; Newcombe and Huttenlocher 2000; Wiegand 1999a; also see Wiegand 1999b for a bibliography that represents a significant body of work on children's understanding of maps), but few studies contribute to our understanding of the mid- and upper-levels of development (e.g., Anderson and Leinhardt 2002; Bausmith and Leinhardt 1998).

Map Reading and Navigation. Map reading and navigation represent practices that bring together not only spatial concepts and tools of representation, but also often includes mental mapping, perspective-taking, and sophisticated processes of reasoning. Additionally it is generally situated in a real-world context (e.g., a natural or built environment) which introduces an entirely new set of variables to consider.

Everyone navigates through the world, with greater or lesser degrees of success. While not culturally universal in its manifestation, navigation is part of every person and every society. We navigate our personal spaces (e.g., offices, homes, bedrooms), our community spaces (e.g. neighborhoods, towns, parks and trails, urban spaces), and foreign spaces (e.g., travel to other places unknown to us). How navigation manifests itself in practice can be different from person to person and from culture to culture. Some individuals prefer to navigate using cardinal directions and grid systems (i.e., survey strategy), while others navigate using landmarks (i.e., route strategy).

Even young children, as early as age four, can successfully identify routes, such as roads and walkways, between two objects on spatial representations (Blades et al. 1998) or navigate mazes successfully (Blades and Spencer 1990). By age six, students can plan routes through complex environments (Sandberg and Huttenlocher 1997). Map alignment issues are a struggle at this age, however (Bluestein and Accredelo 1979). Much like mapmaking, there are few studies between early childhood and adulthood to guide us. However, we know that by adulthood, individuals have developed strategies and processes for navigation (e.g., Lobben 2007, 2004; Golledge 1999; Golledge, Doherty, and Bell 1995).

Geospatial Technologies. Finally, there is a developing, but still small, research base on geospatial technologies, particularly focused on the use of GIS in the K-12 setting or with teachers (e.g., Hong 2014; Demirci, Karaburun, and Ünlü 2013; Huynh 2009; Milton and Alibrandi 2007; Shin 2006; Kerski, 2003; Kim and Bednarz 2013; Wiegand 2003; Meyer, Butterick, Olkin, and Zack 1999). These studies focus largely on high school students and adults (teachers), but can certainly provide some valuable information for determining the upper anchor possibilities integrating geospatial technologies.

Geospatial technologies are particularly an important consideration as they extend the opportunities for students to further their spatial thinking beyond the traditional static representations in classrooms. Geospatial technologies allow students to examine dynamic data at multiple scales and in multiple layers using different formats (remotely-sensed images, aerial or satellite photography, or GIS). They can further their spatial thinking with deep spatial analysis of patterns between multiple layers of spatial data. Geospatial technologies expand the range of possibilities for upper anchors in a learning progression; however, they are a tool and a process and should not be considered in isolation of the spatial concepts and spatial reasoning that would also be part of the learning progression.

Acknowledging the Current Gaps in Spatial Thinking Research

We have alluded to the major gaps we have in the knowledge base on spatial thinking, but we feel it is warranted to discuss these gaps more explicitly.

Lack of K-12 Context. Perhaps most significantly, the majority of research on spatial thinking has primarily been conducted in absence of the K-12 setting, without regard to the context and curriculum that young children are situated within. It often focuses on easily accessible adult populations, often at colleges or universities, or young children (ages 2-4), leaving a large gap in our understanding of the developmental progression.

Small, Fragmented Studies. The research also tends to be studies with small sample sizes and often the methodology changes from one study to the next (e.g., the measurement tasks change; the spatial concepts being studied change). There is very little cross-sectional research that uses the same task across multiple age levels, so consequently we know very little about how individual thinking changes as children grow and learn. An exception to this would be the studies conducted by Golledge and colleagues from grade six through college (Golledge, Marsh, and Battersby 2008a, 2008b; Marsh, Golledge, and Battersby 2007; Battersby, Golledge, and Marsh 2006). The lack of cross-sectional studies across multiple grade levels or longitudinal studies reflects the challenges of conducting studies that follow individual children for months or years or gain access to a range of student populations (which means coordinating multiple school sites, teachers, and classrooms). But a lack of this research goes to the core of what learning progressions are and can be. Without information about how spatial concepts or processes progress over multiple years, and how learning progressions or trajectories vary, we cannot build an empirical basis for a hypothesized learning progression.

Measurements. This debate over early childhood spatial thinking (which has been discussed previously) raises an important methodological question of interest to learning progressions research: Is it tasks themselves that are causing such varied results, or are there more deeply rooted aspects that we just do not fully understand? Much of the ambiguity around measuring spatial thinking can often call the assessment tasks into question. The kinds of measures that we use have been limited. Measures have been limited to one or two spatial concepts or tasks. There are very few studies that have integrated multiple spatial concepts across multiple measures.

We are finding that the types of task chosen to measure spatial thinking might inadvertently favor particular populations over others. For example, Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006) found that different parts of the brain are engaged in solving spatial thinking tasks when they are at the table-top level versus tasks in the real-world. Newcombe (2007) also reports that men tend to perform better on paper-pencil spatial thinking tasks; since a large number of spatial thinking items are paper-pencil, has this led to the common belief that males are better at spatial thinking, or perhaps are the measurements giving us skewed results?

Another concern is the size or scale of the map and of the space that it represents. Most psychological studies have involved small-scale spaces, often the size of a standard living room or smaller. Some geographers, however, (e.g., Montello 1993) stress that there are fundamental differences in the comprehension, perception, and mental representation of spaces at different scales, and thus challenge the claim that information learned in very small spaces will transfer to real-world navigation or map-reading.

Currently choosing measures for spatial tasks is still often a matter of guesswork or anecdotal experience. We need integrated, coordinated measures of constructs that can reveal both group similarities and differences.

Learning Progressions Research to Better Understand Spatial Thinking

In closing, we see learning progressions research as an avenue to provide the much needed systematic and strategic research on spatial thinking that will span across multiple ages and across multiple related concepts and processes. Learning progressions research focuses on coherence and consistency not only in measurement tasks themselves, but also in the iterative process of defining and redefining the progression of development. Learning progressions provide an avenue for collaboration, debate, and consensus among researchers in defining the research domain more clearly and then establishing consistent measurement tasks that can be replicated across grade levels and settings to better understand the development of spatial thinking. Finally, and perhaps most practically, learning progressions on spatial thinking can provide much needed guidance for the development of standards, the design and implementation of instructional materials, and professional development for teachers.

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